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there are many references missing

Chapter 1

The LHC and the ATLAS Detector

1.1 the Large Hadron Collider

+ lead ions?

The Large Hadron Collider (LHC) is a particle accelerator near Geneva, Switzerland. It is 27km in circumference and is located between 45m and 170m underground, crossing the swiss-french border four times. Designed to accelerate two beams of protons to energies of 7 TeV, and to collide these beams at four points along its circumference with an instantaneous luminosity of 10^{34}cm^{-2}s^{-1}.

also, this is the maximum design luminosity. LHC was designed to run at $\mathcal{L}$'s up to this level. The low lumi phase was planned for 10^{33}.

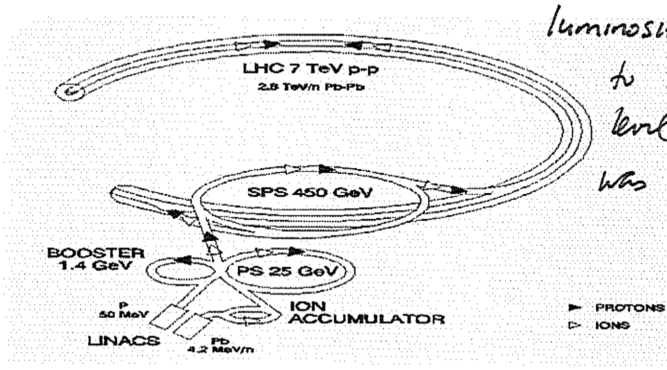


Figure 1.1: Injection chain for protons and ions feeding the LHC.

The injection chain for beam particles is shown in figure 1.1. Hydrogen gas is used as a source of protons. Gas molecules are ionised, and the protons are then accelerated

I don't think it's quite this simple.

you can just say protons here, if you are ignoring lead ions (as above). But you do mention these later on.

at design $\mathcal{L}$, but not yet.

to an energy of 50 MeV in a linear accelerator (LINAC2). A series of synchrotrons (the Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), and Super Proton Synchrotron (SPS)) are then used to accelerate protons to energies of 1.4 GeV, 25 GeV and 450 GeV, respectively. After acceleration by the SPS, beams are injected into the LHC. The LHC beam consists of 2808 bunches, each containing $\sim 10^11$ protons, which are separated in time by 24.95 ns. Superconducting Radio-Frequency (RF) cavities are then used to accelerate the protons to their final energy. At present, protons in the LHC are being accelerated to 3.5 TeV per beam, which is half of the design energy. It is also capable of accelerating heavy ions to high energy, and the ALICE experiment is focused on analysing these collisions.

unnecessarily detailed? People usually just write 40MHz and 25ns, even though strictly speaking you are correct.

put earlier

what about current $\mathcal{L}$? These are relevant for discussions about the presence or absence of pileup in your jet analysis ~~section~~ chapter

1.2 The ATLAS Detector

The ATLAS detector, shown in figure 1.2 is a multipurpose detector used to analyse collisions at the LHC. It is one of two multi-purpose detectors, the other being the Compact Muon Solenoid (CMS). It consists of sophisticated particle tracking systems, ~~several~~ a system of calorimeters, and a muon spectrometer: these are discussed below.

1.2.1 Inner Detector

maybe define ID here so you can use it later on.

The inner detector is used to reconstruct the trajectories (tracks) of charged particles produced during proton-proton collisions. It is comprised of three elements?: the pixel detector, the SemiConducter Tracker (SCT), and the Transition Radiation Tracker (TRT). These three components are contained within a cylindrical region of length 3.5m and radius 1.15m centred on the ATLAS interaction point. The ATLAS solenoid immerses this area in a 2T magnetic field oriented along the z axis. The applied field gives rise to curvature in the trajectories of charged particles, which can then be used to obtain measurements of particle momenta. the curvature only gives you the p_T

odd phrase

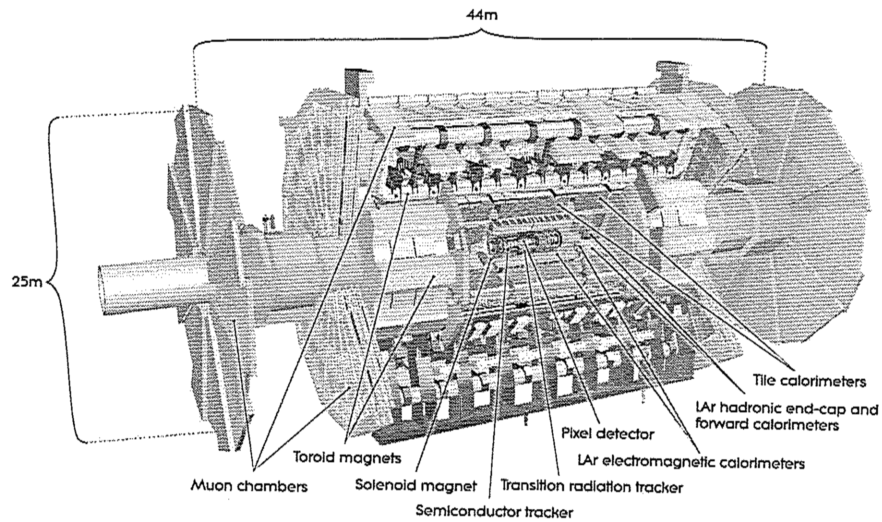


Figure 1.2: Diagram of the ATLAS detector.

The inner detector consists of a barrel section (shown in figure 1.3 and two end cap sections (figure 1.4).

The pixel detector uses sensors ~~are~~ formed from 250μm thick wafers of silicon. The barrel section consists of three cylindrical layers, and three disc like layers are used to form each end cap. All together there are $\sim 8 \times 10^7$ pixel channels, providing a hit resolution of 10 μm in the $R - \phi$ plane and 115 μm in the z direction.

endcap or end-cap would be better.

The SCT is located beyond the pixel detector, and consists of 4 cylindrical layers in the barrel section and 9 disc layers in each end cap. Each SCT module has semiconducting microstrip sensors mounted on both sides. The sensors on either side are oriented at an angle of 40 mrad to each other. As a single microstrip sensor only provides a position measurement in one dimension, orienting two at a slight angle allows the position of the hit to be measured in two dimensions. This gives the SCT a resolution of 17 μm in the $R - \phi$ plane and 580 μm in z.

The TRT is the outermost section of the inner detector, and is formed from drift (straw) tubes. The barrel section contains ~52,500 tubes, while ~123,000 tubes are contained in each end-cap section. Each straw is made from polymide and is 4mm in

polyimide

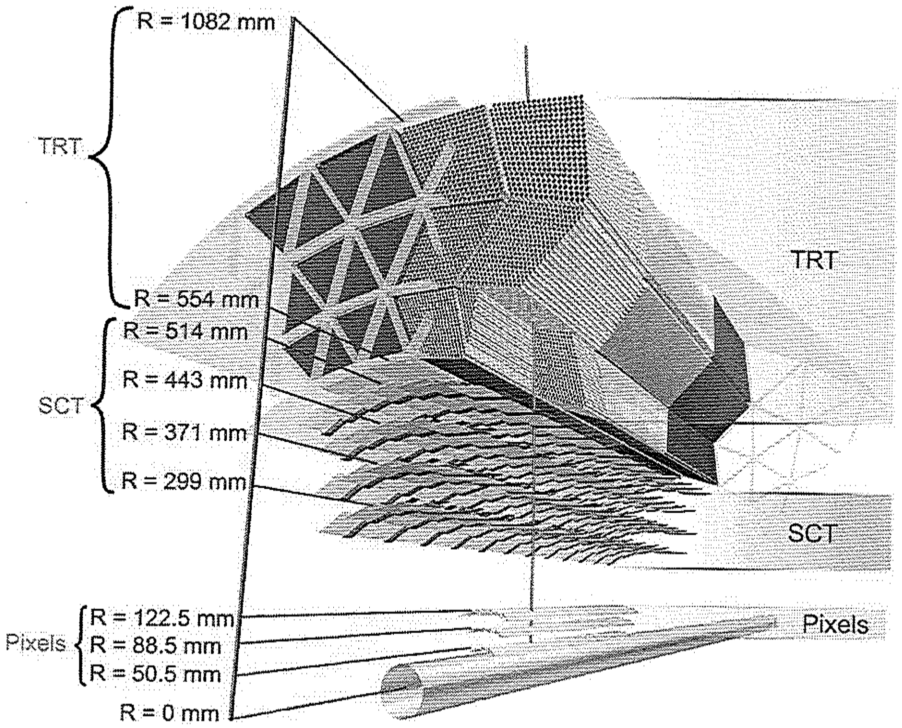


Figure 1.3: Diagram of the barrel section of the inner detector.

diameter, and has a gold plated tungsten wire (with diameter 31 ~~30~~μm) located in the centre of the tube that acts as an anode. The gas in the tubes is made up of 70% Xe, 27% CO_2 and 3% O_2. charged Particles entering the tube ionise the gas, with the resulting electrons drifting towards the anode in the centre. Measurement of the electron drift time allows the distance of the particle track from the wire to be determined with a resolution of 130μm. The straw tubes are housed within a volume filled with CO_2 and a matrix of polypropylene fibres. Electrons moving between the CO_2/polypropylene interfaces will emit transition radiation, which is absorbed by the Xe and leads to an increased signal measured by the straw tubes. The detection of this transition radiation allows the TRT to perform particle identification, discriminating electrons from charged pions.

Where is this discussion from? In the endcap, I believe that foils are used to produce the TR.

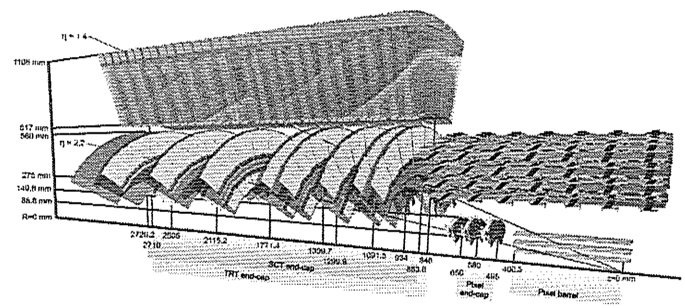


Figure 1.4: Diagram of the inner detector end cap, showing the elements traversed by particles at pseudorapidities of 1.4 and 2.2.

1.2.2 Calorimeters

Atlas does not consist of 5 calorimeters. (not only....). Rewrite

ATLAS consists of five distinct calorimeters, shown in figure 1.5. The Electromagnetic Barrel and Tile calorimeters are located in the central "barrel" section of ATLAS, while the EMEC, HEC, and FCal calorimeters are located within the end cap cryostats at either end.

barrel "section" vs endcap "cryostat". You have not mentioned LAr yet, so it's a bit early to mention cryostats.

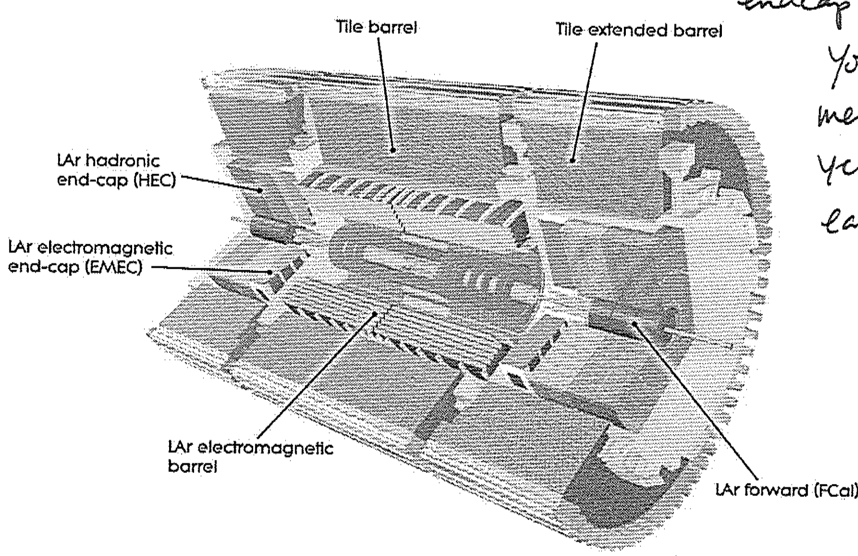


Figure 1.5: The calorimeters of the ATLAS detector.

Barrel calorimeters

why? why?

The EM Barrel (EMB) calorimeter is a lead/liquid argon calorimeter with a distinctive accordion-shaped geometry. It is made up of two half barrel sections ($z < 0$ and $z > 0$), each divided azimuthally into 16 modules. It covers the pseudorapidity range $0 < |\eta| < 1.475$, and is completely symmetric in ϕ.

a schematic view of a section

The diagram in figure 1.6 shows ~~part~~ of the EM barrel calorimeter. The absorber is formed from plates of lead, which are 1.5mm thick for $|\eta| < 0.8$ and 1.1 m thick for $|\eta| > 0.8$. An 0.2mm sheet of stainless steel is glued onto each side of the lead plate in order to increase the mechanical strength of the absorber sheets. These sheets are then folded into the accordion shape. The folding angle increases with depth (radius) in order to maintain the size of the LAr gap throught the calorimeter.

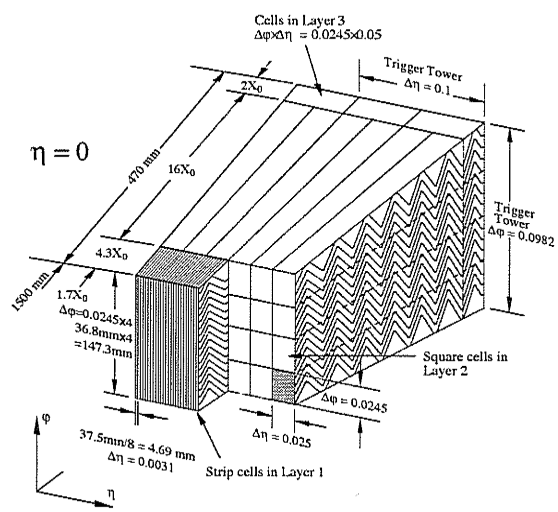


Figure 1.6: Section of the electromagnetic barrel calorimeter, showing the accordion

Flexible Printed Circuit Boards (PCBs) are used to form the electrodes, which consist of three layers of copper separated by polymide. The electrodes are positioned in between layers of the absorber, with honeycomb spacers being used to keep the electrodes in the centre of these gaps. The absorber layers are grounded, while the two outer layers of copper on each electrode are connected to the HV supply. This creates two active liquid

operated at (positive or negative?) high voltage argon gaps of depth 2.1 mm on either side of the electrode. The inner layer of copper on each electrode is used to read out the signal, as it is capacitively coupled to both the outer layers.

(longitudinally)

The readout in the EM Barrel calorimeter [4] is divided radially (longitudinally) into three layers. The first and ~~last~~ third layers are each? a few X_0 in depth and only catch the beginning and end of the shower, while most of the energy is deposited in the second layer which has a depth of $\sim$17-20 X_0. The total depth of the EM calorimeter ranges from 22 to 30 X_0 for pseudorapidities in the range $0 < |\eta| < 0.8$, and from 24 to 33 X_0 in the region $0.8 < |\eta| < 1.3$. The readout granularity in $\Delta\eta \times \Delta\phi$ is 0.003×0.1, 0.025×0.0245, and 0.05×0.0245 in layers 1, 2 and 3, respectively. A diagram of the readout layer of the electrode is shown in figure 1.7, in which the different readout granularities are visible.

defined somewhere earlier in the thesis?

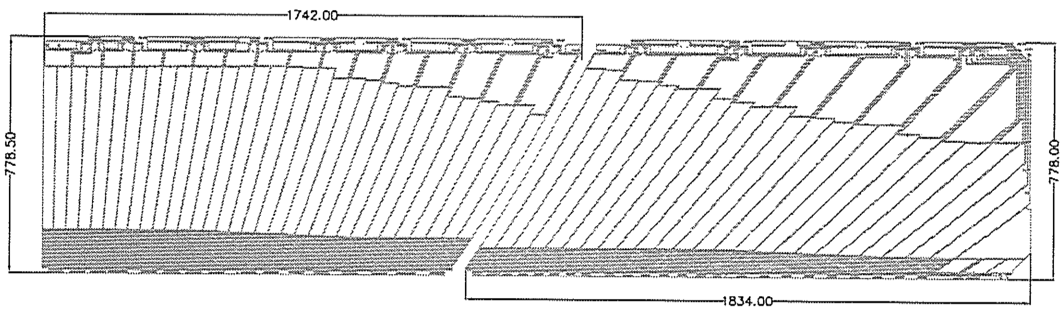


Figure 1.7: schematic view of a Readout layer of an EM Barrel electrode, prior to folding. The ~~piece~~ portion on the left is used to read out signals from $0 < \eta < 0.8$, while ~~the piece~~ that on the right covers the region $0.8 < \eta < 1.475$.

A steel/scintillator "Tile" calorimeter [1] is used to measure the energy of hadronic particles in the barrel region ($|\eta| < 1.7$). It consists of a central barrel section covering the pseudorapidity range $|\eta| < 0.8$, and two extended barrel sections that surround the end cap cryostats. The total depth of the tile calorimeter is 7.4 interaction lengths.

Well, the EM calorimeter is used as well

Each section is divided into 64 modules, each of which covers an azimuthal angle of 5.625°. The absorbing material of the calorimeter is formed from a series of steel "master" plates, which are 5mm thick and run the full radial depth of the tile calorimeter (2.0m).

A series of smaller, 4mm thick spacer plates are positioned in between layers of master plates. The spacer plates are used to create gaps between adjacent master plates, and it is within these gaps that the scintillating tiles are located, as shown in figure 1.8. The scintillating tiles are made of polystyrene, which produces scintillation light in the

is this standard terminology? This does not appear on the figure. Just curious.

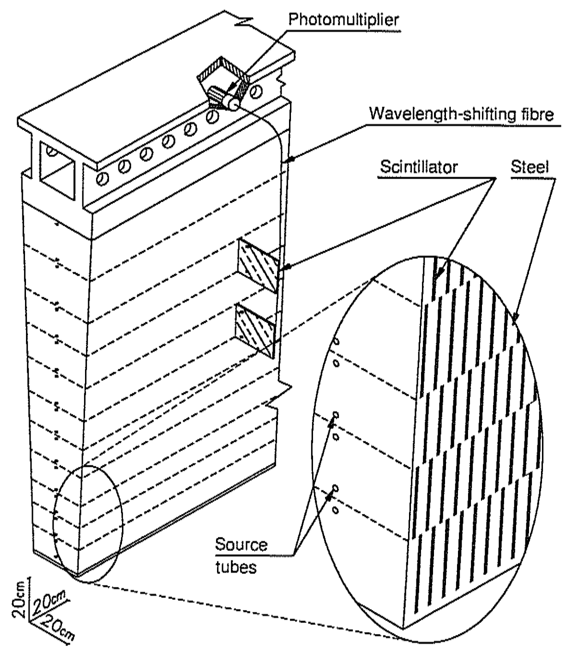


Figure 1.8: Schematic of a tile calorimeter module. Alternating layers of master plates and spacer plates are glued together, with scintillating tiles positioned in the gaps in this structure.

ultra-violet range when excited by the passage of showering particles. The polystyrene is doped with fluors that shift the wavelength of this light into the visible spectrum. Optical fibres are coupled to two sides of each scintillator tile, and are used to carry light from the tiles to the PhotoMultiplier tubes (PMTs). The PMTs then convert the scintillation light to an electronic signal, ~~and are~~ housed within the mechanical support structure of the calorimeter.

rewrite

End Cap calorimeters

The Electromagnetic End Cap (EMEC) and Hadronic End Cap (HEC) Calorimeters are housed within cryostats at either end of the detector. Why?

The EMEC covers the pseudorapidity range $1.375 < |\eta| < 3.2$, and has a similar design to the EM Barrel calorimeter. As with the barrel, the absorber is formed from accordion shaped layers of lead sheets, while the active regions consist of the liquid argon gaps between these layers. Honeycomb spacers are used to keep the electrodes positioned in the centres of these gaps.

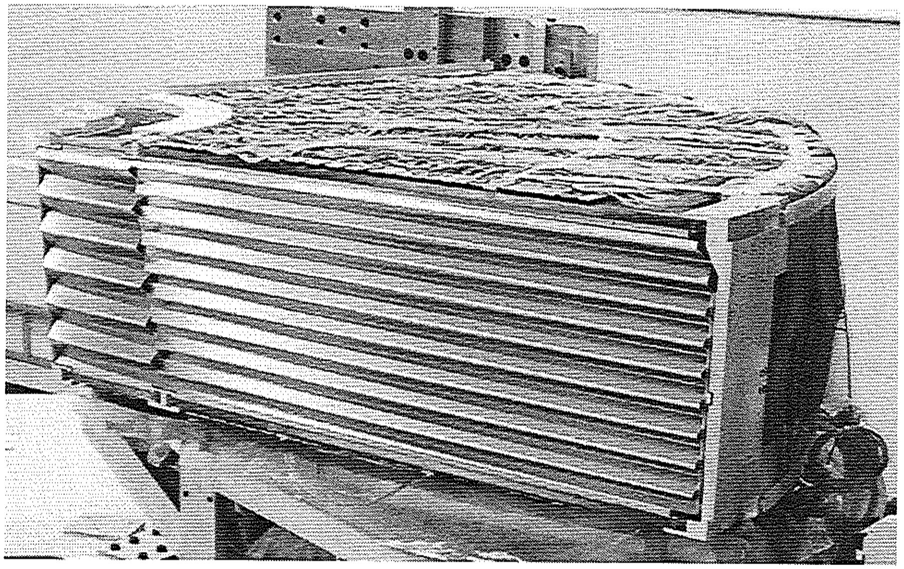
The EMEC ~~is~~ consists of two coaxial wheels, with the boundary between wheels located at $|\eta| = 2.5$. Each wheel is further divided into eight wedge-shaped modules. Due to the accordion shape of the absorber layers, there are no discontinuities in the calorimeter between adjacent modules. As with the EM barrel, the structure of the EMEC is completely symmetric with respect to azimuthal angle. The readout of inner wheel has a granularity of 0.1×0.1 in $\Delta\eta \times \Delta\phi$. The granularity of the outer wheel varies with pseudorapidity, but is at its finest (0.003×0.1) in the region $1.5 < |\eta| < 1.8$.

number of layers also varies w. η. But you don't mention the layers here, though you did for the EMB.

The HEC calorimeters [6] utilise a parallel ~~flat~~ plate geometry, which consists of alternating layers of copper and liquid argon oriented at right angles to the beam. Each section of the HEC is consists a front wheel and a rear wheel, each of which is divided azimuthally into 32 wedge-shaped modules. The front wheel is comprised of a front plate which is 12.5 mm thick, as well as 24 copper plates, each of which is 25mm thick. The rear wheel contains a front plate that is 25mm thick, and is followed by 16 plates of thickness 50mm.

In both wheels, the liquid argon gaps formed between the absorber plates have a depth of 8.5mm. These gaps are then divided into four sub-gaps of depth ~2mm by a set of three parallel electrodes, forming an electrostatic transformer [5]. The signal is read off ~~from~~ a central pad in the middle electrode, with the shapes etched into this pad determining the read-out structure. Cells in the HEC have a granularity of 0.1×0.1 in $\Delta\eta \times \Delta\phi$ for $|eta| < 2.5$, and ~~a granularity of~~ 0.2×0.2 at higher pseudorapidities. $|\eta|$

A wheel is a whole thing in some sense, so how can each "section" correspond to a front and rear wheel? Rewrite this.



not referred to in the text. What purpose does it serve here?

Figure 1.9: photograph of an EMEC module, showing the accordion structure of the absorbers. The boundary between the inner wheel and the outer wheel can be seen towards the left, where the shape of the absorber plate changes.

the detector paper says 4.7

Forward Calorimeters

be more clear!

The ATLAS Forward Calorimeters (FCal) are located next to the beampipe, 4.6m away from the ATLAS interaction point on either side. These are liquid Argon based calorimeters, and are located within a special support tube inside the end-cap cryostat (figure 1.11).

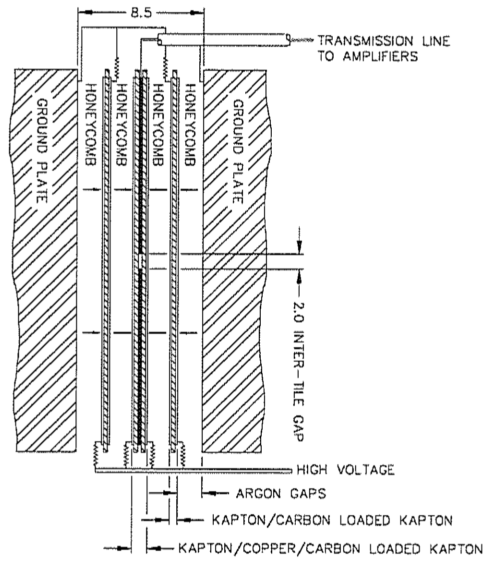
?

~~[illegible]~~ 444 in ~~det~~ FCal paper

The FCal consists of three modules, one electromagnetic module (FCal1) and two hadronic modules (FCal2 and FCal3). Each module has a cylindrical shape, with an outer radius of $450mm$ and a length of $440mm$. A plug made of brass alloy has a similar shape and is located behind the hadronic modules in order to provide additional shielding for the muon chambers behind it. As the FCal operates at a temperature of about 90K in ATLAS, "cold" lengths will be used in the following when quoting dimensions and densities, etc.

quote a more accurate value?

The electromagnetic modules of the FCal were produced by the university of Arizona. Each module consists of a number of circular copper plates with an inner radius of X



not currently referred to in the text

Figure 1.10: Electrode structure in the HEC. Electrodes are arranged to form an electrostatic transformer

Again, I'm not sure this detail is interesting. Or at least more interesting than other details you could provide but do not.

and an outer radius of x. On one side (the ATLAS "A" side, $z > 0$ in the ATLAS coordinate system), the FCal 1 module consists of 18 plates of thickness 24 mm, whereas on the opposite side (the "C" side) 19 slightly thinner plates are used. Each plate is drilled with a hexagonal array of holes into which the electrodes were inserted. Each electrode consists of a copper tube (the cathode) containing a copper rod (anode) around which a PEEK fiber is wrapped. The Inner diameter of the copper tubes is 2.62 mm while the diameter of the copper rods is 2.35mm, thus leaving a gap of 267 μm which is filled with liquid Argon. The PEEK fiber has a diameter of 250 μm, and is present to keep the rod positioned in the centre of the tube, thus maintaining the uniformity of the LAr gap throughout the electrode + electrical isolation of the rod & tube. Typical gap sizes used in LAr calorimeters are on the order of a few millimetres, however as the FCal is located at high pseudorapidity, minimum bias events will deposit energy in it at a very high rate. The smaller gap size is required

these numbers are radii not diameter

There is some discussion of the FCal structure that does not need to be described for particular modules. You could have an introductory part when you give the overview of the FCal dimensions & basic structure.

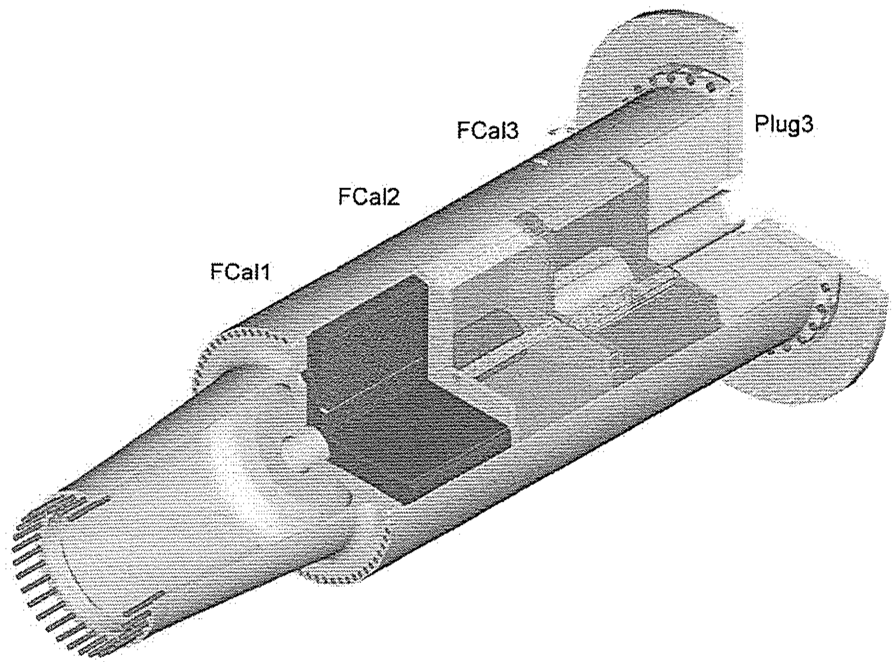


Figure 1.11: Cut-away view showing the FCal within its support tube (taken from [3]).

why is that a problem?

in order to reduce the drift time across the gap, and thus preventing the high rate of ionization from causing a build-up of positive ions in the liquid argon. The distance between electrodes in FCal1 is similar to the Molière radius (a measure of the lateral spread of an electromagnetic shower) for copper. EM showers in the FCal should thus spread across several electrodes, allowing the calorimeter to sample the shower effectively. Copper also allows the FCal1 module to conduct heat efficiently. This is important, as it prevents the energy deposited within the FCal from raising the temperature of the liquid argon above its boiling point.

this could be in an introductory section on the FCal structure since it applies to all modules.

The hadronic modules of the FCal were produced at the University of Toronto (FCal2) and at Carleton University in Ottawa (FCal3). Each of these modules uses two copper end plates drilled with a hexagonal array of holes, each of which holds an electrode. The electrodes in these cases use copper tubes for their anodes but rods made of pure tungsten (with density 19.2) for the ~~cathodes~~. The absorb~~ing~~ matrix is formed from small

units anodes or

as illustrated in fig 1.12

slugs of tungsten alloy ("WFeNi" - 97% tungsten/2% Iron/1% Nickel) positioned in the gaps between the electrode tubes. The material composition and density of the calorimeter components are important factors when defining the geometry of the calorimeter in simulations. By themselves, the WFeNi slugs have a density of 18.3 g/cm^3. When considering the WFeNi slugs, the copper electrode tubes, the tungsten rods and any spaces in the absorber matrix that are filled with liquid argon, the average density of absorbing material in the hadronic modules is 14.33 g/cm^3 for FCal2 and 14.45 g/cm^3 for FCal3 [7]. ~~A diagram showing the way in which the WFeNi slugs are positioned amongst the electrodes is shown in figure 1.12~~

properties "geometry" is jargon in this context

Calculated to be?

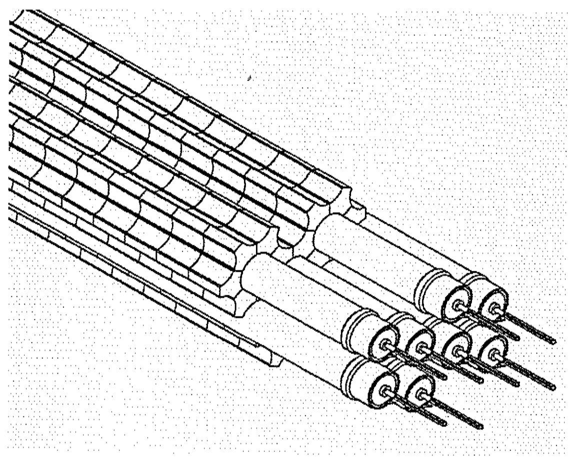


Figure 1.12: Diagram showing the arrangement of electrodes and slugs in the hadronic modules ~~(taken from~~ [3]~~)~~.

this should also come earlier

As charge is deposited in the liquid argon, it drifts due to the electric field present in the electrode, causing a current which is used as a signal. The electronics chain used to read out and process this signal is discussed in detail in section ??.

1.2.3 Muon Spectrometer

The muon spectrometer is the outermost system of the ATLAS detector, and is illustrated in figure 1.13. It is capable of measuring muon momenta in the region $|\eta| < 2.7$, with

quantity	FCal1	FCal2	FCal3
Absorber material	Copper	Tungsten	Tungsten
Module inner diameter	720 mm	790 mm	860 mm
Electrode Separation	7.5mm	8.62 mm	9.0mm
Rod Diameter	2.35 mm	2.47 mm	2.75 mm
Tube inner diameter	2.62 mm	2.84 mm	3.25 mm
LAr Gap	267 μm	375 μm	500 μm
distance from IP to front face	4668.5mm	5128.3 mm	5602.8

Table 1.1: Dimensions of the FCal modules.

a momentum resolution of $\sim$ 10% at 1 TeV, and can trigger on muons with $|\eta| < 2.4$. The muon spectrometer is comprised of four types of sensors: Monitored Drift Tubes (MDTs), Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs). The MDTs and CSCs are used to measure the kinematics of muons, while the TGCs and RPCs are used for triggering. (but also contribute to the track reconstruction)

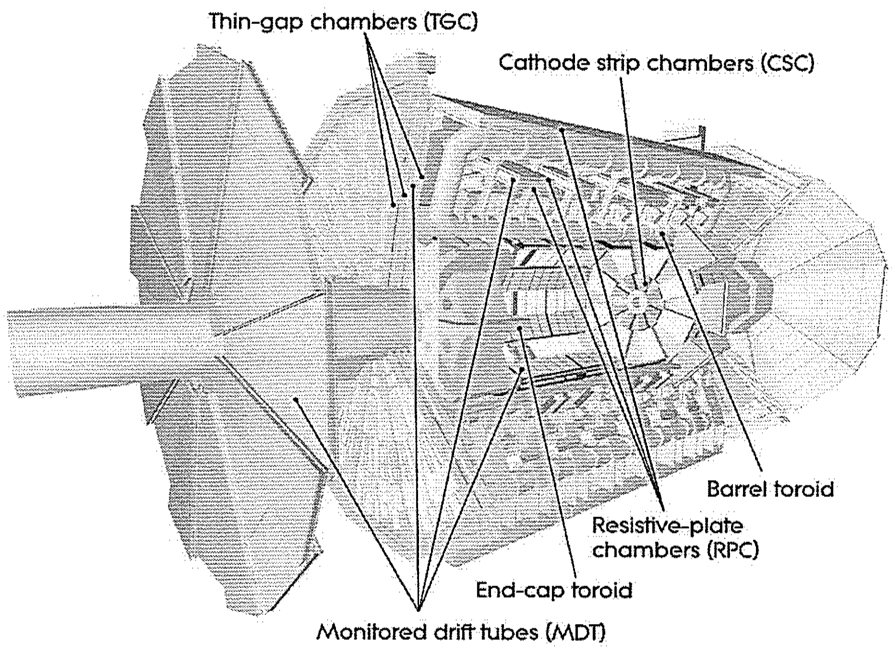


Figure 1.13: The different components of the Muon spectrometer. The MDT and CSC components are used for measuring muon

The toroid magnets (located in the barrel and end caps) produce a toroidal field, which causes charged particles to bend in the $R-z$ plane. In order to measure track momenta with high resolution, the alignment of the MDT and CSC chambers must be well known. A high precision optical system is used to measure the positions and mechanical deformations of the measurement chambers, which must be known to within 30 μm in order to achieve the desired momentum resolution.

MDTs are comprised of cylindrical drift chambers of diameter 29.97mm, with a central anode wire of diameter 50μm. A mixture of Argon (93%) and CO_2 (7%) is used to fill the tubes. Each tube is capable of measuring the distance of a muon track to the anode wire with a resolution of 80μm. Arranged in three layers in the barrel and two in the end cap. not a sentence.

?

In the end cap sections, the innermost layer of measurement chambers is made up of CSCs. the MDTs are unable to withstand the high levels of radiation present at these

isn't η the issue, rather than z?

locations ($|z| \sim 7$m), and so CSCs are used instead. These are multi-wire proportional chambers (MWPCs), filled with a mixture of Argon (80%) and CO_2 (20%). The CSCs are capable of measuring hit position to within 60 μm in the bending plane, achieving the desired momentum resolution.

For triggering purposes, RPCs are used in the barrel region ($|\eta| < 1.05$) while TGCs (which are a form of MWPC) are used in the end cap region ($1.05 > |\eta| > 2.4$). The intrinsic response time of these detectors is on the order of a few nanoseconds, enabling them to reliably identify the bunch crossing in which any detected muons were produced.

we have already been running at twice this rate for some time.

1.2.4 Trigger and Data Acquisition

Collisions between proton bunches occur at ATLAS at a rate of 40MHz, whereas the maximum rate at which event data can be recorded is 200Hz. The trigger system is in place in order to ensure that as many interesting events are recorded as possible, while rejecting less interesting events. The ATLAS trigger system consists of three consecutive levels: level

↳ will there somewhere (in your introductory or QCD chapters) be the usual plot of cross-sections for the various QCD & EW processes?

one (L1), level 2 (L2), and the Event Filter (EF). The L1 trigger selects candidate events at a maximum rate of 75 kHz. Some of these events are subsequently rejected at L2, reducing the acceptance rate to 3.5 kHz. The final level of event rejection is done by the EF, which accepts events at the desired rate of 200 Hz.

The L1 trigger utilises custom-built hardware, and needs to decide whether to accept or reject the event within 2.5 μs of the corresponding bunch crossing. The level 1 trigger consists of three of three parts, L1 Calo, L1 muon, and the Central Trigger Processor (CTP). The L1 Calo trigger is used to select electrons, jets, taus, and other high p_T objects, while the L1 muon trigger processes signals from the RPCs and TGCs of the Muon spectrometer.

The CTP decides whether an event is accepted or rejected at L1. Trigger conditions are specified in a "menu", where each object on the menu is some combination of trigger items from L1Calo and/or L1Muon. The CTP also handles the prescales on menu objects, which are used to control the bandwidth allowed for each item and keep the L1 acceptance rate at the desired level. For a menu item with a prescale of 50, one event will be accepted at L1 for every fifty events that satisfy the trigger conditions associated with that menu item. Menu items associated with a rare or particularly interesting event topology may be given a prescale of one, in which case the event is accepted every time the trigger conditions are met. Frequently occurring or less interesting topologies (such as those containing low pt jets) are given higher prescales.

The available time in which the L1 decision must be made is too short for L1Calo to consider the information from all individual calorimeter cells, and so readouts from these cells are grouped together to form trigger towers. In the barrel and end cap regions ($|\eta| < 3.2$), these trigger towers have a granularity 0.1×0.1 in η and ϕ. The level 1 central jet trigger combines 2×2 blocks of trigger towers to form "jet elements", which then have a granularity of 0.2×0.2 in $\eta - \phi$ space. A sliding window algorithm is then used to identify jets [2]. The window consists of a 4×4 grid of jet elements, and a jet is reconstructed if the total Et within the window exceeds a given threshold. For example, the "L1_J10" algorithm requires the transverse energy in the in the window to exceed 10 GeV. Additionally, the $2x2$ cluster of jet elements in the centre of the window is required to be a local maximum, that is, the central cluster must have a transverse energy greater than that of any other 2×2 block of jet elements within the window.. If these criteria are met, then the event is accepted by the jet algorithm. The 0.4×0.4 area of $\eta - \phi$ at the centre of the window is then identified as a "Region of Interest" (ROI), and is passed on to any relevant L2 trigger algorithms.

(FJ)

The forward-jet trigger is used to identify jets in the region $|\eta| > 3.2$, and operates independently of the central jet trigger. While the central jet trigger uses information from the EM Barrel, tile, EMEC and HEC calorimeters, the forward jet trigger relies only on the FCal. Trigger towers in the FCal have a granularity of 0.4×0.4 in $\eta - \phi$, which is coarser than in other calorimeters. A jet element is then formed by summing all FCal trigger towers in η, such that the jet element has dimensions 1.2×0.4 in η and ϕ, respectively. Jets are then identified using the same sliding window algorithm as the central jet trigger.

Where does the 1.2 come from?

algorithms?

At L2, the trigger decision needs to be made within 40ms. This interval is sufficient for cell based methods to be used, although only cells within the region of interest (about 2% of the detector) are read out. A cone-based algorithm is used for jet identification: a cone of fixed radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is positioned at the centre of the RoI. Energy weighted values of η and ϕ are obtained by summing cells within the cone, and the centre of the cone is then moved to these coordinates. This process carried out a predetermined number of times.

where is the 2% from? Is that a typical single RoI?

At the EF level, 4.0s of processing time is available, and so algorithms similar to those used for offline reconstruction (described in section XX) may be used at the trigger level. Note that the EF was not online while taking the data used in this analysis.

be specific since you have not started to discuss analysis.

trigger hardware? EF nodes? (how many)

maybe refer back (or ahead) to wherever jet algorithms are discussed.

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